Physics Letters B 714 (2012) 197–214

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for supersymmetry with jets, missing transverse momentum and at least one hadronically decaying τ lepton in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector ☆

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ARTICLE INFO

Article history:
Received 17 April 2012
Received in revised form 19 June 2012
Accepted 23 June 2012
Available online 27 June 2012
Editor: H. Weerts

Keywords:
Supersymmetry
GMSB
Tau lepton

ABSTRACT

A search for production of supersymmetric particles in final states containing jets, missing transverse momentum, and at least one hadronically decaying τ lepton is presented. The data were recorded by the ATLAS experiment in $\sqrt{s} = 7$ TeV proton–proton collisions at the Large Hadron Collider. No excess above the Standard Model background expectation was observed in 2.05 fb^{-1} of data. The results are interpreted in the context of gauge mediated supersymmetry breaking models with $M_{\text{mess}} = 250$ TeV, $N_5 = 3$, $\mu > 0$, and $C_{\text{grav}} = 1$. The production of supersymmetric particles is excluded at 95% C.L. up to a supersymmetry breaking scale $\Lambda = 30$ TeV, independent of $\tan\beta$, and up to $\Lambda = 43$ TeV for large $\tan\beta$.

1. Introduction

Supersymmetry (SUSY) [1–9] is a well-motivated theoretical concept that introduces a symmetry between bosons and fermions. As a consequence, every Standard Model (SM) particle has a SUSY partner with the same mass and quantum numbers except for the spin which differs by half a unit. Since none of these partners has been observed SUSY must be a broken symmetry if realized in nature. If R-parity is conserved [10–14], SUSY particles can only be produced in pairs and would decay through cascades involving lighter SUSY particles. These decay cascades end in the production of the lightest supersymmetric particle (LSP), which is stable and escapes the detector unseen, giving rise to missing transverse momentum in the detector. SUSY can remedy various shortcomings of the Standard Model, such as the hierarchy problem [14–19], the lack of a dark matter candidate [20,21] and the non-unification of the gauge couplings [22–25]. To achieve this, the masses of at least some SUSY particles must be near the weak scale, and therefore, if weak-scale SUSY is realized in nature, there are good prospects to discover it at the Large Hadron Collider (LHC).

In certain SUSY models, large mixing between left and right sfermions, the partners of the left-handed and right-handed SM fermions, implies that the lightest sfermions belong to the third generation. This leads to a large production rate of τ leptons from decays of $\tilde{\tau}$ sleptons and gauginos, the partners of the SM gauge bosons, in SUSY cascade decays. For example, in the context of Gauge Mediated SUSY Breaking (GMSB) [26–31] the lighter of the two $\tilde{\tau}$ sleptons is the next-to-lightest supersymmetric particle (NLSP) for a large part of the parameter space, and the very light gravitino, $\tilde{G}$, is the LSP. Hence $\tilde{\tau}$ sleptons decay to a τ lepton and a gravitino. While this $\tilde{\tau} \to \tau\tilde{G}$ process is the dominant source of τ leptons from SUSY decays in certain regions of GMSB model parameter space, the analysis presented here is sensitive to any process producing τ leptons in association with jets and missing transverse momentum.

This Letter presents a search for supersymmetry in final states with at least one hadronically decaying τ lepton, missing transverse momentum and jets with the ATLAS detector at the LHC. The results of the search are interpreted within the GMSB model. Previous experiments at LEP [32–34] have placed constraints on $\tilde{\tau}$ and $\tilde{e}$ masses and on more generic GMSB signatures. Among these the limits from the OPAL experiment [32] were the most stringent, excluding $\tilde{\tau}$ NLSPs with masses below 87.4 GeV. The D0 Collaboration performed a search for squark production in events with hadronically decaying τ leptons, jets, and missing transverse momentum [35], and the CMS Collaboration performed searches for new physics in same-sign ditau events [36] and multi-lepton events [37] including τ pairs, but the GMSB model was not specifically considered in any of these results. A search for supersymmetry in final states containing at least two hadronically decaying

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http://dx.doi.org/10.1016/j.physletb.2012.06.061

τ leptons, missing transverse momentum, and jets with the ATLAS detector is presented in another Letter [38].

2. ATLAS detector

The ATLAS detector [39] is a multipurpose particle physics apparatus with a forward–backward symmetric cylindrical geometry and nearly 4π coverage in solid angle.[1] The inner tracking detector consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The inner detector is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field and by high-granularity liquid-argon sampling calorimeters. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. A muon spectrometer consisting of large superconducting toroids and a system of precision tracking chambers surrounds the calorimeters.

3. Data and simulated samples

The analysis is based on data collected by the ATLAS detector in proton–proton collisions at a center-of-mass energy of 7 TeV between March and August 2011. Application of beam, detector, and data-quality requirements resulted in an integrated luminosity of $2.05 \pm 0.08\ \text{fb}^{-1}$ [40,41]. The data were collected using triggers based on one jet with transverse momentum $p_{\text{T}} > 75$ GeV, measured at the raw electromagnetic scale, and missing transverse momentum above 45 GeV.

In GMSB models, the breaking of SUSY is mediated through flavor-blind SM gauge interactions of messenger fields with mass scale M_{mess} which is small compared to the Planck mass. In addition to M_{mess}, the free parameters in GMSB models are the scale of the SUSY breaking, Λ, the number of messenger fields, N_5, the sign of the Higgsino mixing parameter, $\text{sign}(\mu)$, the scale factor for the gravitino mass, C_{grav}, and the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$. In this analysis, GMSB models are studied in the Λ–$\tan\beta$ plane for fixed $M_{\text{mess}} = 250$ TeV, $N_5 = 3$, $\text{sign}(\mu) = +1$ and $C_{\text{grav}} = 1$. The chosen set of parameter values restricts the analysis to specific final states relevant for the search with τ leptons and to promptly decaying NLSPs. For $N_5 \geqslant 2$ and large $\tan\beta$ the lightest $\tilde{\tau}$ slepton, $\tilde{\tau}_1$, is the NLSP.

Samples of simulated GMSB events are generated with the `Herwig++` [42] generator for ten values of Λ in the range $10 \leqslant \Lambda \leqslant 85$ TeV and ten values of $\tan\beta$ in the range $2 \leqslant \tan\beta \leqslant 45$, with the SUSY mass spectra generated using `ISAJET 7.80` [43]. The `MRST2007 LO*` [44] parton distribution functions (PDFs) are used. The production cross sections are calculated with `PROSPINO` [45–48] to next-to-leading order in the QCD coupling using the next-to-leading-order `CTEQ6.6` [49] PDF set. The two samples with $\Lambda = 30$ (40) TeV and $\tan\beta = 20$ (30), which have cross sections of 1.95 (0.41) pb, are used as representative points for the optimization of the event selection.

The dominant background processes in this search are production of W and Z bosons in association with jets ($W+\text{jets}$ and $Z+\text{jets}$), top quark pair ($t\bar{t}$) and single top quark production. The $W+\text{jets}$ and $Z+\text{jets}$ production processes are simulated with the `ALPGEN` [50] generator, using the `CTEQ6L1` [51] PDF set, and are normalized to a cross section of 31.4 nb and 9.02 nb [52–54], respectively. The $t\bar{t}$, single-top and diboson production processes are generated with `MC@NLO` [55] and the `CTEQ6.6` [49] PDF set, and are normalized using a cross section of 0.165 nb, 0.085 nb [56–58] and 0.071 nb [59,60], respectively. Parton showers and hadronization are simulated with `HERWIG` and the underlying event is modeled with `JIMMY` [61]. The programs `TAUOLA` [62,63] and `PHOTOS` [64] are used to model the decays of τ leptons and the radiation of photons, respectively. The production of multijet events is simulated with `PYTHIA` [65], though the multijet background yield in this analysis is estimated using data. All simulated samples are processed through a full simulation of the ATLAS detector [66] based on GEANT4 [67]. To match the pile-up (overlap of several interactions in the same bunch crossing) observed in the data, the generated signal and background events are overlaid with minimum-bias events [68,69] and the resulting events are reweighted so that the distribution of the number of interactions per bunch crossing agrees with the data.

4. Object reconstruction

Jet candidates are reconstructed with the anti-k_t clustering algorithm [70] with radius parameter $R = 0.4$. The inputs to this algorithm are clusters of calorimeter cells seeded by cells with energy significantly above the measured noise. Jets are constructed by performing a four-vector sum over these clusters, treating each cluster as a four-vector with zero mass. Jets are corrected for calorimeter non-compensation, upstream material, and other effects using p_{T}- and η-dependent correction factors obtained from Monte Carlo simulation and validated with extensive test-beam and collision-data studies [71]. Only jet candidates with $p_{\text{T}} > 30$ GeV, $|\eta| < 2.8$ and a distance $\Delta R > 0.2$ with respect to the nearest identified electron are considered as real hadronic jets, where the distance is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

The electron and muon identification criteria are identical to those in Ref. [72]. Electrons and muons are only considered if they satisfy $p_{\text{T}} > 20$ GeV and $\Delta R > 0.4$ with respect to the nearest identified jet.

The magnitude of the missing transverse momentum, $E_{\text{T}}^{\text{miss}}$, is computed from the vector sum of the transverse momenta of all identified electrons and muons, all jets, and remaining clusters of calorimeter cells with $|\eta| < 4.5$ [73].

Hadronically decaying τ leptons are reconstructed from jet candidates with $p_{\text{T}} > 10$ GeV and are distinguished from quark- or gluon-initiated jets using a boosted decision tree (BDT) based on eleven discriminating shower-shape and tracking variables [74]. Electrons are further rejected using transition radiation and calorimetric information. An energy calibration factor for hadronically decaying τ leptons is applied as function of p_{T} and η. Candidates are required to satisfy $p_{\text{T}}^{\tau} > 20$ GeV and $|\eta| < 2.5$ and to have one or three associated reconstructed tracks (prongs) with total charge ± 1. The τ candidates are required to satisfy a p_{T}-dependent BDT output criterion [74] chosen to give $\sim 30\%$ ($\sim 50\%$) signal efficiency for one-prong (three-prong) τ candidates as estimated in $Z(\to \tau\tau) + \text{jets}$ events. The BDT selection has a corresponding background acceptance of $\sim 0.5\%$ ($\sim 3\%$), estimated in dijet events, and the different selection criteria reflect different abundances of one- and three-prong jets in background samples.

During a part of the data-taking period, an electronics failure in the liquid-argon calorimeter created a dead region in the second and third layer of the calorimeter, corresponding to approximately 1.4×0.2 rad in $\Delta\eta \times \Delta\phi$. A correction is made to the jet energy using energy depositions in cells neighboring the dead region; events having at least one jet, including the leading τ candidate, in this region for which the corrected energy is above 30 GeV are discarded, resulting in a loss of $\sim 6\%$ of the data sample.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the z-axis coinciding with the axis of the beam pipe. The x-axis points from the interaction point to the center of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

5. Event selection

Events are required to have a reconstructed primary vertex with at least five associated tracks with $p_T > 500$ MeV. Events are rejected if they contain identified electrons or muons or if any jet or τ candidate is consistent with arising from detector noise or non-collision background [71]. Events are required to contain one or more identified τ candidates, at least two jets, one with $p_T > 30$ GeV and another with $p_T > 130$ GeV, and missing transverse momentum $E_T^{miss} > 130$ GeV. The latter two requirements ensure that the trigger efficiency is above 98% in both data and simulation.

The two jets leading in p_T are required to be separated in azimuth from the direction of the missing transverse momentum by more than 0.3 rad. This requirement reduces multijet events, which typically have instrumental missing transverse momentum aligned with the leading jets. Multijet events are further suppressed by requiring $E_T^{miss}/m_{eff} > 0.25$, where the effective mass, m_{eff}, is defined as the scalar sum of E_T^{miss}, the p_T of the two leading jets, and the p_T^{τ} of the leading τ candidate.

Events are required to have a transverse mass, m_T, above 110 GeV. The transverse mass is defined as

$$m_T = \sqrt{m_\tau^2 + 2p_T^\tau E_T^{miss}\left(1 - \cos\Delta\phi\left(p_T^\tau, E_T^{miss}\right)\right)},$$

where $\Delta\phi(p_T^\tau, E_T^{miss})$ is the azimuthal angle between the τ and the direction of the missing transverse momentum. This requirement suppresses backgrounds due to $W+$jets and top-quark production. The remaining SM backgrounds are further suppressed by requiring $m_{eff} > 600$ GeV. This is the final selection defining the signal region for the analysis. The m_T and m_{eff} requirements as well as the criteria used for the suppression of multijet events are chosen to maximize the signal significance computed with the Asimov approximation [75].

6. Background estimation

Background processes are divided into three classes which are estimated separately: events with true τ leptons from $t \to b\tau\nu$ decays (both top-quark-pair and single top quark production) and $W(\to \tau\nu)+$jets events; events with misidentified ('fake') τ candidates in top, $W+$jets, and $Z+$jets events; and events with fake τ candidates in multijet events. The two fake-τ classes are treated separately to account for differences in τ misidentification probabilities due to different event topologies and jet composition.

Events with true τ leptons are estimated in a control region defined by replacing the requirement on the transverse mass in the final selection with the requirement $m_T < 70$ GeV. For events with a correctly reconstructed τ lepton and with E_T^{miss} entirely due to a single neutrino, m_T is kinematically bounded from above by the W mass, within the detector resolution; by requiring $m_T < 70$ GeV, more than 90% of the events in the resulting control region are expected to contain true τ leptons from top-quark and W decays. The composition of the event sample in this control region is given in Table 1. Within this control region, the background due to Z decays is estimated from simulation and the remaining small background due to multijet events is estimated using a procedure similar to that used to estimate the multijet background in the signal region, described below.

Within the $m_T < 70$ GeV control region, top-quark and $W+$jets yields are estimated individually with a maximum-likelihood fit to the output distribution of a BDT built from four variables: the number of b-quark jets, the total jet multiplicity, the transverse momentum of the second-leading jet, and the transverse thrust T of the event, defined as $T = \max_{\hat{n}}\{\sum_i \hat{n}\cdot\vec{p}_{T,i}/|\sum_i \vec{p}_{T,i}|\}$, where i runs over the missing transverse momentum and all jets, excluding the tau candidates, with transverse momentum vectors $\vec{p}_{T,i}$, and the transverse thrust axis is given by the unit vector $\hat{n}$ for which the maximum is attained. Top-quark events have more reconstructed b-quark jets, a higher jet multiplicity, higher jet momenta, and tend to be more spherical than $W+$jets events. Jets containing b quarks are identified with about 60% efficiency, evaluated with top-quark events, using secondary vertex reconstruction and three-dimensional impact parameters of tracks associated with the jet [76]. The output distribution of this BDT is shown in Fig. 1 along with the results of the fit. The results of the fit are scale factors for $W+$jets and top quark backgrounds which reflect differences in cross sections and reconstruction efficiencies between data and simulation. The measured scale factors are 1.22 ± 0.13 for top events and 0.71 ± 0.03 for $W+$jets events. These scale factors are applied to simulated event samples in the signal region to derive the final expected true-τ yields from background processes.

For the estimation of backgrounds due to fake τ candidates in top-quark, $W+$jets, and $Z+$jets events, a second control sample is defined by selecting events that fulfill the event selection but with modified criteria on m_T and m_{eff}: $m_T > 70$ GeV and either $m_T < 110$ GeV or $m_{eff} < 600$ GeV. Since the m_T distribution falls off rapidly above the W mass for true-τ events, the intermediate m_T region selected here is relatively enhanced in fake-τ events, and the overall composition of this region is expected to be very similar to that of the signal region. Multijet events are expected to make up less than 3% of this sample and are estimated from

Table 1
Numbers of observed and expected events in the true-τ-dominated W/top control region, defined as $m_T < 70$ GeV. The numbers shown for $W+$jets and top are from Monte Carlo simulation and do not include the correction factors derived from this control region. The correction factors obtained from a fit to data are 1.22 ± 0.13 for top and 0.71 ± 0.03 for $W+$jets. The true-τ purity is 97% for top, 96% for $W+$jets and 87% for $Z+$jets.

Top	$W+$jets	$Z+$jets	Multijet	Data
186.4 ± 8.4	919 ± 40	62.2 ± 6.7	1.8 ± 1.8	951

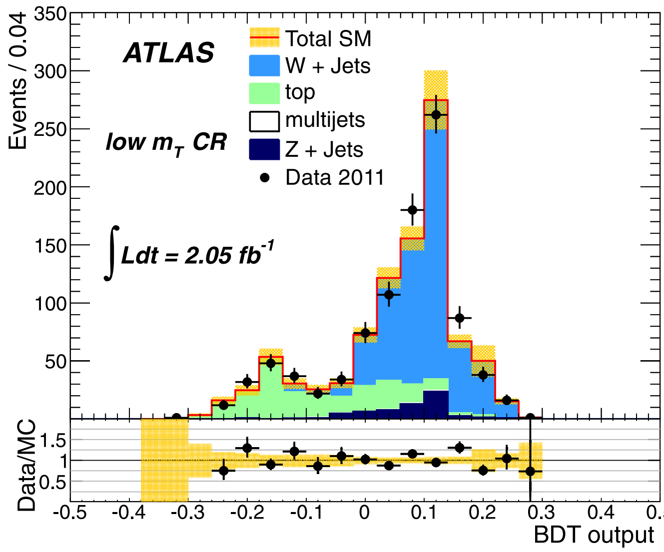

Fig. 1. Output distribution of the BDT used to discriminate $W+$jets from top-quark events in the low-m_T control region, defined as $m_T < 70$ GeV. Background distributions are taken from simulation. The yield for $W+$jets and top backgrounds are taken from a maximum-likelihood fit to this distribution. The solid (red) line with shaded (yellow) error band corresponds to the total SM prediction, while the points are data. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

Table 2
Numbers of observed and expected events in the fake-τ-enhanced control region. The numbers of expected $W+$jets and top-quark events have been corrected by the correction factors measured in the true-τ-dominated region. The fake-τ correction factor obtained from data is 0.50 ± 0.08.

	True τ	Fake τ	Total
Top	53.3 ± 7.5	37.8 ± 5.8	91.1 ± 9.4
$W+$jets	80.5 ± 6.9	33.3 ± 4.1	113.8 ± 8.0
$Z+$jets	5.1 ± 1.6	41.5 ± 10.8	46.6 ± 10.9
Multijet	0 ± 0	2.9 ± 1.0	2.9 ± 1.0
Total	139 ± 10	116 ± 13	254 ± 17
Data			197

simulation. The composition of the fake-τ-enhanced sample in this control region is shown in Table 2. Within this control region, true-τ backgrounds are subtracted using estimates derived from the true-τ-dominated control region. The numbers of events remaining after the true-τ subtraction are used to determine a scale factor, 0.50 ± 0.08, which is then applied to simulated samples of fake-τ events in the signal region to obtain a final background estimate. While this scale factor differs significantly from unity, it is consistent with other ATLAS studies of the performance of τ fake rates in simulation.

Backgrounds due to multijet events are estimated in a third control region in which either $E_T^{miss}/m_{eff} < 0.25$ or one of the two leading jets is aligned in azimuth with the missing transverse momentum direction. Within this sample, the probability for jets (which contain very few true τ leptons) to satisfy the τ selection criteria is estimated by applying the selection to randomly chosen jet candidates. This probability is then applied to a complementary sample of multijet events, where the azimuthal separation and E_T^{miss}/m_{eff}, as well as all other event selection requirements, match those of the signal region, but where the τ candidate is again randomly chosen from among the jet candidates. This provides an estimate of the multijet background yield in the signal region. It is found that the multijet background makes up only a few percent of the total SM background in the signal region.

Possible contamination from SUSY signals has been considered in all three background-estimation control regions and is found to have a negligible effect on the results presented below.

7. Systematic uncertainties

Dominant systematic uncertainties on the estimated background yields are due to uncertainties in the jet energy scale (3–8%) [71], jet energy resolution (6–13%) [71], τ energy scale (2–10%) [74], statistical uncertainties in the data control regions (5–15%), and Monte Carlo uncertainties related to the extrapolation from the control regions to the signal region (10–20%). This last term includes statistical uncertainties in the simulation, variations in the in the assumed $W+$jets/top/$Z+$jets mixture in the fake-τ control region, and Monte Carlo generator uncertainties (estimated by varying the shower matching, factorization and renormalization scales, α_s, and the amount of initial-state and final-state radiation) [77]. Additional uncertainties on $W+$jets and top-quark backgrounds are estimated by varying the assumed b-quark identification efficiency within measured uncertainties (4–11%) [76]. Uncertainties on the multijet background yield are estimated by studying correlations between m_{eff} and the azimuthal separation between the leading two jets and the missing transverse momentum. Additional systematic uncertainties, including those on the pile-up description in the simulation, are considered and found to be negligible.

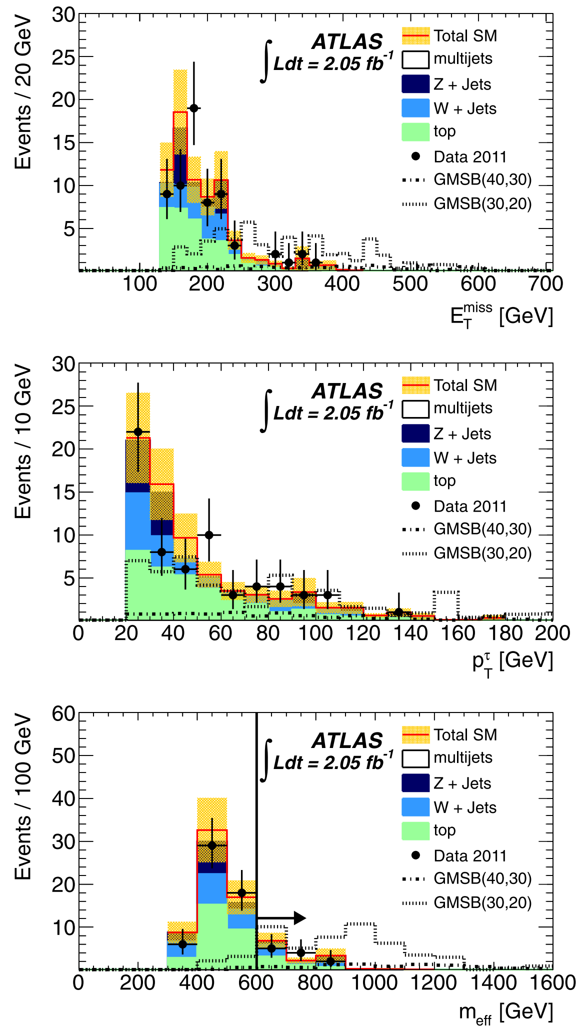

Fig. 2. Distributions of E_T^{miss}, p_T^{τ}, and m_{eff} for data with all selection requirements except for that on m_{eff}, along with the corresponding estimated backgrounds. Backgrounds are taken from simulation and normalized with control regions in data. The solid (red) line with shaded (yellow) error band corresponds to the total SM prediction, while the points are data. The error bands indicate the size of the total (statistical and systematic) uncertainty. The notation GMSB(40, 30) stands for the GMSB model with $\Lambda = 40$ TeV and $\tan\beta = 30$ and analogously for GMSB(30, 20). (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

In addition to the sources described above, systematic uncertainties on the SUSY signal cross section are estimated by varying the factorization and renormalization scales in PROSPINO up and down by a factor of two, by considering variations in α_s, and by varying the proton PDFs within their uncertainties. These theoretical uncertainties total typically 8–12% across the relevant region of parameter space. Uncertainties are calculated separately for individual SUSY production processes.

8. Results

Fig. 2 shows the distributions of E_T^{miss}, p_T^{τ}, and m_{eff} for data with all selection requirements applied except for that on m_{eff}, along with the corresponding estimated backgrounds. The numbers of expected SM background events and the observed number of events after the m_{eff} requirement are shown in Table 3. The data agree with the background expectation.

Based on these results, limits are placed on contributions beyond the SM to the signal region. With 11 events observed and

Table 3
Expected SM background event yields and number of events observed in data after the final requirement on m_{eff}. All systematic uncertainties are included here, and the uncertainty on Σ_{SM}, the sum of all SM backgrounds, takes correlations between the individual background uncertainties into account. The true-τ purities are 53% and 64% for the top and $W+$jets backgrounds, respectively, and are negligible for the $Z+$jets and multijet backgrounds. For comparison, the estimated event yield for a GMSB signal with $\Lambda = 40$ TeV, $\tan\beta = 30$ is an additional 9.1 ± 1.7 events.

Top	$W+$jets	$Z+$jets	Multijet	Σ_{SM}	Data
5.6 ± 1.4	4.7 ± 1.5	2.4 ± 0.7	0.5 ± 0.6	13.2 ± 4.2	11

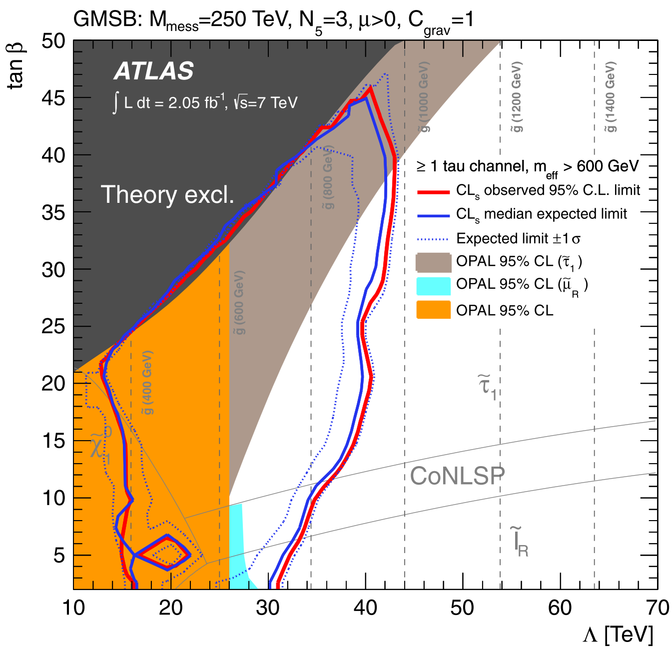

Fig. 3. Expected and observed 95% C.L. exclusion limits in the $M_{\text{mess}} = 250$ TeV, $N_5 = 3$, $\mu > 0$, $C_{\text{grav}} = 1$ slice of GMSB, together with the most stringent previous limits from OPAL [32]. The identity of the NLSP is indicated, with CoNLSP the region where the $\tilde{\tau}$ and $\tilde{\ell}$ are nearly degenerate.

13.2 ± 4.2 expected, an upper limit of 8.5 on the number of events observed due to non-SM sources is derived at 95% confidence level (C.L.). This limit corresponds to an upper limit on the visible cross section of 4.0 fb, where the visible cross section is defined as the product of production cross section, branching fraction to at least one τ lepton, acceptance, and efficiency using the event selection defined in Section 5. For the two benchmark points $\Lambda = 30$, $\tan\beta = 20$ and $\Lambda = 40$, $\tan\beta = 30$ the product of branching ratio to τ-leptons, the acceptance and the efficiency for this selection amounts to 1.47% and 1.69%, respectively. Fig. 3 shows an interpretation of the result as a 95% C.L. exclusion limit in the $M_{\text{mess}} = 250$ TeV, $N_5 = 3$, $\mu > 0$, $C_{\text{grav}} = 1$ slice of the GMSB model. Fig. 3 also shows the variation of the expected limit in response to $\pm 1\sigma$ fluctuations in the expected SM background and the SUSY cross sections. The excluded regions are calculated using a profile likelihood method with systematic uncertainties modeled as varying Gaussian-distributed nuisance parameters [78,79]. The resulting limit is compared with previous exclusion limits from searches for $\tilde{\tau}$ and $\tilde{e}$ production and GMSB topologies at LEP. The region of small Λ and large $\tan\beta$ is theoretically excluded since it leads to tachyonic states. In this model, the production of supersymmetric particles can be excluded at 95% C.L. up to $\Lambda = 30$ TeV, independent of $\tan\beta$, and up to $\Lambda = 43$ TeV for large values of $\tan\beta$.

9. Conclusions

In conclusion, this Letter presents a search for supersymmetry in final states containing jets, missing transverse momentum, and at least one τ lepton with the ATLAS experiment in $\sqrt{s} = 7$ TeV proton–proton collisions at the LHC. This is the first search in these final states at the LHC that includes events with one τ lepton. No excess of events is seen beyond the expected Standard Model backgrounds in 2.05 fb^{-1} of data. Limits are placed on the visible cross section and in the context of GMSB models. The limits obtained extend the results from previous experiments.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Gerece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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